High efficiency multi-junction solar cell design

Amit Kumar Senapati, Manjit Bahadur Singh

Abstract— Energy from the sun is the best option for electricity generation as it is abundantly available everywhere and sustainable source. Advance of Photovoltaic (PV) technology in recent years has made solar energy one of the practical alternative energy sources available in the energy market. In order to make the PV energy more affordable and cost effective, major focus of the research community and industry is improvement on power efficiency of PV systems. Early stage of solar panel manufacturing known as process technology plays a crucial role in achieving above limits. This paper presents a novel process technology for solar panel with 6 junctions.

Index Terms—Solar,multi-junction cells,renewable energy,photovoltaic.

I. INTRODUCTION

Over the last few decades, there have been significant changes in the way people use the world's energy resources. There has been an increasing effort from governments, industry and academic institutions to find alternative sources of energy and to improve energy efficiency. This, plus an ever growing pressure from different sectors of society to reduce carbon dioxide emissions, has motivates the development of emerging technologies to reduce the dependency on fossil fuels and the optimization of existing systems in order to minimize energy consumption.

Although this advance was not enough to drive investments in this type of cell, it encouraged some groups to remain in this area. During this period, the greatest interest focused on mono-crystalline silicon, amorphous silicon and other semiconductor materials. It was only in 1990, with the announcement of the results of a laboratory scale cell with a conversion efficiency of 35% (in areas of 5mm2), that the polycrystalline silicon cell manufacturing technology became really interesting. This advance led to renewed investments in research to produce low-cost polycrystalline silicon [3]. The consequences of these research efforts are illustrated in Fig. 1, which shows that, up to 1996, the market was dominated by the production of mono-crystalline silicon panels. The advances in polycrystalline silicon cell technology resulted in an inversion in the tendency of the curve in 1997, led, for example, by the 1996 publication presenting a panel with 15% conversion efficiency [4].
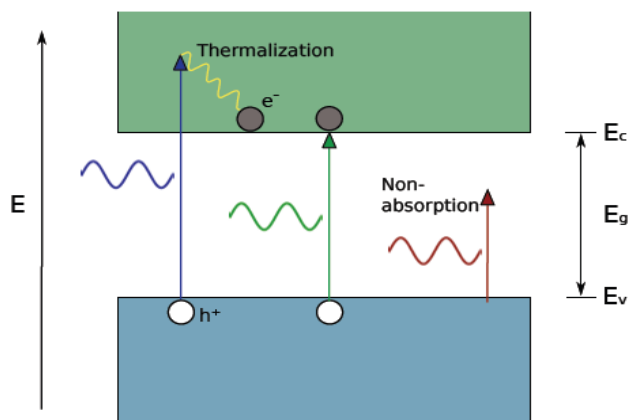
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Fig.1:Generation mechanism

Basically, until 1997, the silicon employed in the production of polycrystalline solar cells originated mostly from waste produced by the microelectronics industry. Considering the magnitude-scale differences, differences in silicon specification requirements for application in microelectronics and in the area of PV, and the costs involved in the process, special interest has focused on the search for more economic routes for the production of PV silicon. Moreover, in the last 5 years, largely due to the rising price of crude oil and to growing awareness of the need to protect the environment, major investments began to be made in this technology [6].

There are two ways to produce electricity from the sun [5]. First is by using the concentrating solar thermal system. This is done by focusing the heat from the sun to produce steam. The steam will drove a generator to produce electricity. This type of configuration is normally employed in solar power plants. The other way of generating electricity is through a photovoltaic (PV) cell. This technology will convert the sunlight directly into electricity. This technique is now being widely installed in the residential house and at remote places. It is also contributing to the significant increase in the development of Building Integrated Photovoltaic (BIPV) system.

Energy Source Max	Power (TW)
Total surface solar	85 000
Desert solar	7650
Ocean thermal	100
Wind	72
Geothermal	44
Biomass	7
Tidal wave	4

TABLE 1: Power available from renewable resources [2]

This paper consists of four parts: chapter-1 is introduction. Chapter-2 shows history of solar panel, chapter-3 describes proposed model, chapter-4 shows simulation results and some limits. Finally chapter-5 represents references we followed.

II. BASIC SOLAR PANEL

Contrary to intuition, a solar cell resembles a steam engine in more ways than one would suspect. Despite the obvious differences in appearance, applications and operation mechanism, both these energy conversion devices are ultimately limited in their efficiency by the same laws of thermodynamics. These laws can be applied to solar cells, the same as for any other energy conversion device, to obtain an upper limit on efficiency that is independent of most material parameters. It turns out that, just as for an old-fashioned steam engine, a solar cell is ultimately limited by the Carnot efficiency. Such a thermodynamic description of a solar cell can be very convenient when compared to conventional methods of modeling solar cell efficiencies, which employ material parameters such as carrier diffusion length and lifetimes, because it allows for a fast assessment of the cells performance.

A. Exact model

The detailed balance model is based on the statistical balance of electron-hole generation and recombination.

$$J_{out} = q(F_i - F_{rec}) \tag{1}$$

Here, Jout is the current that is extracted from the cell, Fl is the rate of generation of electron-hole pairs due to absorption of incident light, and Frec is the total rate of carrier recombination, which is assumed to be at least partly radiative. q denotes the elementary charge. Note that all currents here are expressed in current per unit cell area. From this equation current voltage characteristics can be derived, as well as the efficiency of the solar cell which is the starting point of our analysis. Carrier recombination rate Frec and generation rate Fl shall be discussed below, after which an expression for the cell efficiency will be derived.

- **Carrier Recombination**

The second term Frec is the carrier recombination rate, which we assumed to be zero in the calculation of _ult. It can be written here as:

$$F_{rec} = R_{rec}^{rad} + R_{rec}^{non-rad} \tag{2}$$

with R_{rec}^{rad} and $R_{rec}^{non-rad}$ being the radiative and non-radiative recombination rate, respectively. The radiative recombination rate originates from the cells blackbody radiation, more specifically it is the part of the cells blackbody spectrum that lies above the band gap energy. For an emitter with emissivity tc and a back reflector this is given as [2].

However, a p-n junction solar cell under illumination is not in thermal equilibrium, and the photon chemical potential is equal to the separation of the electron and hole quasi-Fermi levels [7]. This can be understood by considering that the chemical potential is defined as the free energy brought to the system by the addition of a photon, other than the photon energy hγ. This free energy comes from the relaxation of the carriers from their exited state, with which an energy is associated equal to the separation between the quasi-Fermi levels. This separation also equals qV, where V is the voltage over the cell [7]. We thus obtain the following expression for

$$R_{rec}^{rad} = t_c \frac{2 \epsilon_c}{c^2 h^3} \int_{E_g}^{\infty} \frac{E^2}{e^{\frac{E-qV}{KT_c}} - 1} dE \tag{3}$$

The non-radiative recombination rate $R_{rec}^{non-rad}$ is not easily obtained. Its origins compose of Auger recombination, bulk defect recombination and surface defect recombination. One can use an explicit expression to account for Auger recombination [10], or even an empirical expression for bulk defect and surface defect recombination [5], but this makes the analysis more complex and calculation time significantly longer. Moreover, the former two recombination types are device-dependent and therefore not relevant in the calculation of a theoretical upper limit to the efficiency. In stead, we could use the external quantum efficiency (EQE) of radioactive

- **Carrier Generation**

The first term on the right side of Eq. 1, Fl, is the rate of generation of carriers due to the absorption of incident light and is given by:

$$F_l(E_g) = t_s C Q_s(E_g) \tag{4}$$

ts is the probability that an incoming photon with E≥ Eg creates an electron-hole pair, and depends on the reflectivity of the cell, the absorption coefficient of the material and light trapping in the cell. In this work we shall not consider the effect of these parameters, so we shall set ts to unity. This can be realized in practice by using state of the art antireflection coatings [13] and a cell that is sufficiently thick or employs effective light trapping [14].

C denotes the concentration factor of the sunlight, and is a dimensionless quantity. C is 1 for un-concentrated sunlight under normal incidence, and has a maximum value of _ 46000. This maximum is given by the ratio of the maximum irradiance of light falling on a planar surface (π) and the irradiance of the sunlight on earth. For sunlight under normal incidence, the latter is given by:

$$\epsilon_s = \pi \sin^2(\theta_s) \tag{5}$$

with

$$\theta_s = \sin^{-1}\left(\frac{R_{sun}}{D_{sun}}\right) \tag{6}$$

So that

$$\epsilon_s = \pi \frac{R_{sun}^2}{D_{sun}^2} \tag{7}$$

Here, θ_s denotes the angle that the edge of the sun makes with the normal vector to the surface of the solar cell, analogues to $\theta_s$lim for emitted light. Rsun and Dsun are the radius of the sun and the distance between the earth and the sun, respectively. Cmax is then:

$$C_{max} = \frac{\pi}{\epsilon_{sun}} = \frac{D_{sun}^2}{R_{sun}^2} \approx 46000$$

i.e. a concentration of 46000 suns.

- Efficiency

With this information on the carrier generation and recombination, we can now set out to derive an expression for the efficiency of the cell. The incoming power Ps per unit area on the solar cell is given by Eq. 4. The output power of the solar cell is defined as the product JoutV . The efficiency is then

$$\eta = \frac{VJ_{out}}{P_s}$$
$$= \frac{qV}{P_s}(F_i - R_{rec}^{rad} - R_{rec}^{non-rad})$$
$$= \frac{qV}{P_s}\left[F_i - R_{rec}^{rad}\left(1 + \frac{\pi}{\epsilon_c \, t_c x} - \frac{\pi}{\epsilon_c \, t_c}\right)\right]$$
(8)

To obtain the maximum efficiency of a cell with Eg given, $\boldsymbol{\eta}$ must be optimized by varying V .

Eq. 13 is an exact result and applies to all types of illumination spectra and concentration factors. It is however a laborious procedure to optimize _ with respect to Eg using this model, particularly for multi-junction solar cells where multiple band gaps need to be varied

Above radiative recombination can more appropriately linked using External Quantum Efficiency(EQE) as follows.

For this purpose, we define the parameter x as the EQE for a cell with tc = 1 and θlim = 90:

$$x \equiv \frac{R_{rec}^{rad,\pi,1}}{R_{rec}^{rad,\pi,1} + R_{rec}^{non-rad}}$$
(9)

where $R_{rec}^{rad,\pi,1}$ is the radiative recombination rate for tc = 1, then

$$R_{rec}^{non-rad} = R_{rec}^{rad,\pi,1}\left(\frac{1-x}{x}\right)$$
$$= \frac{\pi}{\epsilon_c \, t_s}R_{rec}^{rad}\left(\frac{1-x}{x}\right)$$

III. PROPOSED MODEL

A. If we consider the case where we have a solar cell that consists not of a single p-n junction but of multiple junctions with different band gaps that each absorb a different part of the solar spectrum, our expression for the efficiency should be slightly modified. The analysis is slightly different for cells with tandem geometry than for cells with a spectrum splitting device [7], but we shall only concern ourselves with the latter. Furthermore, we shall assume that the ideal diode approximation is valid, such that the single cell efficiency is correctly described by Eq. 8.

For the i-th sub cell in a multi-junction solar cell with band gap Ei

$$J_{sc}^i = qt_s CQ_s^i$$
(10)

where

$$Q_s^i = \int_{E_g^i}^{E_g^{i-1}} S(E)\,dE$$

This expression assumes that there is some perfect mechanism for splitting the solar spectrum, directing each part of the spectrum to the corresponding sub-cell without any losses. The dark current is denoted by:

$$J_0^i = R_0^{rad,i}\left(\epsilon_c, t_c, E_g^i\right)\left(1 + \frac{\pi}{\epsilon_c \, t_c x} - \frac{\pi}{\epsilon_c \, t_c}\right)$$
(11)

$$R_0^{rad,i}\left(\epsilon_c, t_c, E_g^i\right) = t_c \frac{2\,\epsilon_c}{c^2 h^3}\int_{E_g}^{\infty} \frac{E^2}{e^{\frac{E}{KT_c}}}\,dE$$

We assume that C, tc, ts and ^{x} do not differ between the sub-cells.

Finally, with these expressions for J_{sc}^i and J_0^i the efficiency of the N-junction solar cell is:

$$\eta = \frac{1}{P_s}\sum_{i=1}^{N} FF^4 \; V_{oc}^i \; J_{sc}^i$$
(12)

B. Methods

Here spectrum splitter technique is used to design multi-junction solar cell. There exist currently two different designs for such a multi-junction solar cell: the tandem cell geometry, where the different sub-cells are stacked on top of each other, and the spectrum splitter geometry, where some spectrum splitting device distributes the light of different wavelengths to the sub-cells [7, 15]. The first design requires the materials to be epitaxial grown on top of each other. This severely constraints the choice of materials and makes fabrication expensive. Also, because the sub-cells are connected in series, one has to match the currents of the sub-cells, which limits the efficiency. The spectrum splitter design has the advantage that the sub-cells are disconnected and can be operated individually, which means that one has full flexibility in the choice of materials, no current matching is necessary and fabrication can be less expensive. Several spectrum splitter designs have been realized and have been demonstrated work in practice [16, 17]. In this work we shall not focus on the design of the spectrum splitter, merely on the efficiency that can be obtained using its principles. Therefore it is assumed that the spectrum splitting occurs without losses.

C. Optimization Procedure for Ideal Efficiency Limits

In the first part of this work, we optimize band gap values for solar cells with 1 to 8 junctions to find their maximum possible efficiency. We take ^{x} = 1. Optimization occurs as follows.

Band gap values of each sub-cell are varied in steps of 0.2eV and cell efficiency is calculated for every combination of band gaps $\{E_g^1, E_g^2, \dots E_g^i\}$. This gives us a maximum efficiency and corresponding optimum band gap values.

This optimum is then further refined by repeating the operation, varying the band gaps Eig now in steps of 0.01eV

in   the   domain

$$\left[E_{g,opt}^{i} - 0.05eV, E_{g,opt}^{i} + 0.05eV\right]$$

Where $E_{g,opt}^{i}$ is the optimum value for the i-th band gap as found by varying the band gaps in steps of 0.2eV. This method of optimization is illustrated in Fig. 2 for the case of the ultimate efficiency of a single junction cell. In this way, optimum band gap values and maximum efficiency are found for:

1. The ultimate efficiency: $\boldsymbol{\eta}_{ult}$
2. The efficiency under maximum concentration: $\boldsymbol{\eta}C_{max}$
3. The efficiency for no concentration or angular restriction: $\boldsymbol{\eta}C=1$

D. Material Requirements

The materials that we propose must obey the following criteria:

- ✓ They do not contain rare chemical elements.
- ✓ The elements that are contained must be obtainable in an economically feasible manner, that is they
must exist in high concentrations in e.g. ore.
- ✓ They do not contain highly poisonous elements, such as Cd or Hg.

The materials should have as high as possible absorption coefficients for photon energies above the band gap. Secondly because high absorption coefficients usually also indicate low radiative lifetimes, resulting in a higher quantum efficiency of radiative recombination. They are not known to contain high defect densities, which would result in high non-radiative recombination rates.

Using the band gap energies of the materials thus found, we then study efficiency of single junction and multi-junction cells depending on the parameters mentioned above: the number of junctions, concentration C, limiting output angle θ_lim and ꭓ.

IV. SIMULATION AND CONCLUSION

We consider first the single junction c-Si cell, where we discuss the origin of the losses that occur and the improvements of its efficiency that are possible by using concentration or angular restriction. The same analysis is then carried out for a 6-junction Ge-(c-Si)-CZTS-(a-SiC)-GaP-GaAs cell. In this section, _ is set to unity and band gaps were optimized to find maximum values for the ultimate efficiency $\boldsymbol{\eta}$_ult, the efficiency for maximum concentration and the efficiency for no concentration or angular restriction. This was done for 1 to 8 junction solar cells, for both the case where all sub-cell band gap energies were varied, as well as the case where three of the band gaps were set to the band gaps of germanium (0.67 eV), crystalline silicon (1.12 eV) and amorphous silicon (1.7 eV). Efficiency obtained were also compared to literature. The results are shown in Fig. 5.
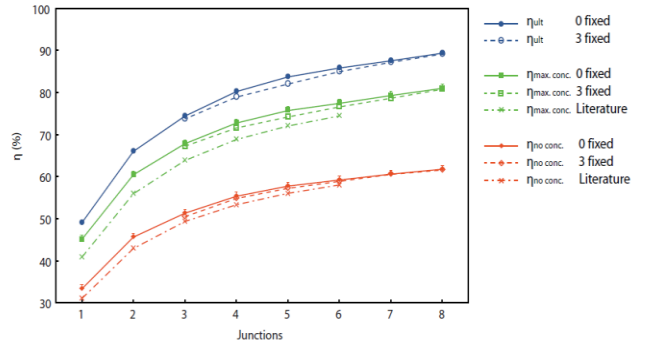

Figure 2: Maximum efficiency for solar cells with 1 to 8 junctions

are shown. Also, results are shown for the case where all band gaps were varied (full lines) as well as the case where 3 band gaps were set to the 0.67 eV, 1.12 eV and 1.7 eV (the band gaps of Ge, c-Si and a-Si, respectively) and the other band gaps were varied (dashed lines). The dot dashed lines represent values found in literature [7], where an ideal blackbody spectrum was used for the solar radiation.

Firstly, it can be seen in Fig. 5 that the efficiency increases continuously with the number of cell junctions, however the increase in efficiency per junction added becomes low after 4 or 5 junctions (_ 2% efficiency per junction). It indicates that the origin of the increase of efficiency is the reduction of thermalization and non-absorption losses, which are the only losses present in all three types of efficiency. These losses are strongly reduced by the addition of a second or a third junction to the cell, which allows for a much larger part of the spectrum to be efficiently absorbed, whereas reduction of these losses saturates for addition of more than 4 or 5 junctions

Secondly, setting 3 band gap energies to those of Ge, c-Si and a-Si does not seem to have a dramatic effect on efficiency. Differences are usually of the order of 1 %. This can be interpreted in two ways: either the band gaps of c-Si, a-Si and Ge are close to the optimum band gap values that were found, or alternatively the maximum efficiency is not a very sharp maximum and there exist many combinations of band gaps that reach almost the same efficiency. In any case, this is a positive result, as it allows for the use of these well-characterized semiconductors in the design of the solar cell.

Thirdly, the difference in efficiency can be attributed to the blackbody radiation from the cells, grows with the number of junctions, from 3.4 % for a single junction cell to 8.4 % for a cell with eight junctions. This behavior can be understood by realizing that each sub-cell adds its own blackbody radiation to that of the total cell, since the area of one sub-cell is constant irregardless of the number of sub-cells. This means that for example an 8-junction cell has an area twice as large as a 4 junction cell, and therefore more blackbody radiative losses. This effect decreases the efficiency slightly for higher number of junctions, causing the growing difference between the blue and the green graph. Because of this, it is also expected that after a certain number of junctions (assuming that the area of a sub-cell remains constant, as we have done here), the efficiency will decrease, because the reduction of thermalization and non-absorption losses no longer compensates for the increased blackbody radiation.

Fourthly, it can be observed that the increase in efficiency due to concentration grows with the number of junctions, from 11.8 % for a single junction cell to 19.2 % for eight junctions. This is due to two effects: Firstly the thermalization losses, which are the main constraint on efficiency for a single junction cell, are decreased for higher number of junctions, allowing for more improvement of efficiency by concentration. Secondly, concentration is most effective for cells with narrow band gaps, which are present more in cells with high number of junctions. This is because the difference in Voc between cells with maximum concentration and no concentration

$$\frac{KT_c}{q}\ln(C_{max}) = 0.278V$$

This is a larger relative increase of Voc for cells with lower band gap, which may have a Voc as low as 0.3 V (for Eg :0.5 eV) under un-concentrated illumination. Therefore, for these sub-cells, concentration can cause roughly a doubling of output power.

Finally, maximum efficiency lie above literature values. Differences are 4% for maximum concentration and 2.5% for no concentration. This difference is however expected, since for these literature values an ideal blackbody spectrum was taken for the solar irradiation, whereas we have used the AM1.5 D spectrum. This produces higher efficiency, as one can reduce thermalization losses and non-absorption losses by tuning the band gaps such that they match the peaks and dips in the spectrum, absorbing most efficiently in areas of the spectrum with high intensities. It is shown by Baruch et al. [4] that the difference in maximum efficiency due to these different spectra, in the case of a single junction cell with no concentration, is 3%.

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